REPORT OF WORK PERFORMED

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Title: Development of High Strength Concrete Using Less Energy Intensive Materials

24 pp

INTRODUCTION

The terms semi-lightweight or sand-lightweight are commonly employed to describe concretes made with natural sand and structural lightweight aggregate meeting the requirements of ASTM C 330. Semi-lightweight concrete like other forms of concrete depends for its strength on a low water/cement ratio. In this investigation, a superplasticizing admixture is used to achieve relatively low water/cement ratios at a relatively high level of workability (100 mm slump), thus increasing the strength potential of the matrix without loss of workability. The effect of varying the composition of the cementitious matrix in terms of proportions of cement and fly ash is also examined. Since fly ash is a by-product of the firing of electric power generating plants with powdered coal, its cost is not energy-related, in contrast to cement where almost half the cost derives from the energy consumed in firing the kiln. Not only are fly ashes cheaper and less energy-intensive materials than cement, but they also have excellent cementitious properties, particularly those in Western Canada. This allows fly ashes to substitute for a significant proportion of the cement normally required without loss of concrete strength and with some saving in direct costs.

MATERIALS

Cement

A single batch of Type I cement purchased fresh from the Exshaw plant of Canada Cement Lafarge was employed in the main program. Cost in Calgary

about $101.00 per tonne. Chemical and physical properties shown in Table 1 were supplied by the manufacturer. Mortar cube strengths determined in our laboratory were 22.3 MPa at 3 days and 28.7 MPa at 7 days.

TABLE 1 - Chemical Analysis of Cement

Oxide Composition		Compound Composition	
SiO_2	21.16	C_3S	52.1
Al_2O_3	4.34	C_2S	21.4
Fe_2O_3	2.65	C_3A	7.0
CaO	62.70	C_4AF	8.1
Free lime	0.32		
MgO	3.80		
Na_2O	0.16		
K_2O	0.73		
SO_3	2.83		
Ign. loss	1.05		

Admixtures

1. Normal strength Darex for air-entrainment.
2. Mighty 150 for increasing workability from 25 mm nominal slump to 100 mm nominal slump. Specific gravity 1.2.

Sand

Normal weight natural sand supplied by Consolidated Concrete Ltd. with a fineness modulus of 2.56. Sieve analysis in Table 2 is yearly average for 1980 provided by the supplier.

TABLE 2 - Sieve Analysis of Sand

Sieve Size	Cumulative Percent Retained	Passing
No. 4	2.2	97.8
8	11.7	88.3
16	24.3	75.7
30	43.9	56.1
50	78.4	21.6
100	95.3	4.7
200	97.9	2.1

Lightweight Aggregate

Herculite, an expanded shale of ½ in. (13 mm) maximum size manufactured by Consolidated Concrete Ltd. Sieve analyses are given in Table 3a. Other properties given in Table 3b were determined in our laboratory. Consignment 1 was used in trial mixes and consignment 2 employed throughout the main series of mixes.

TABLE 3a - Sieve Analyses of Lightweight Aggregate

Sieve size - in.(mm)	Cumulative Percent[1] Retained	Passing	Cumulative Percent[2] Retained	Passing
½ in. (13 mm)	0.8	99.2	2.6	97.4
⅜ in. (10 mm)	39.2	60.8	45.3	54.7
No. 4	94.6	5.4	92.6	7.4
No. 8	97.7	2.3	94.7	5.3

(1) Monthly average for Jan. 1981 provided by the supplier.

(2) Sample from consignment 2 tested in our laboratory.

TABLE 3b - Properties of Lightweight Aggregate

Property	Consignment		
	No. 1 (Oct. 1980)	No. 1 (Dec. 1980)	No. 2 (Feb. 1981)
Dry Unit Weight (loose)	804 kg/m^3	880 kg/m^3[a]	-
Dry Unit Weight (rodded)	833 kg/m^3	936 kg/m^3[a]	988 kg/m^3[a]
Absorption	13.85%	9.84%	12.80%
Porosity	-	35.1%[b]	32.4%
Bulk S.G.	1.305	1.511	1.576
Bulk S.G. SSD basis	1.486	1.659	1.778
Apparent S.G.	1.593	1.774	1.974

[a] mean of three tests

[b] mean of two tests

Fly Ash

A product obtained from the Forestburg plant in Alberta and refined and marketed by Consolidated Concrete Ltd. Cost in Calgary currently (March 1981) $38.50 per tonne, which includes a haul of about 160 miles. Chemical and physical properties in Table 4a and 4b provided by the supplier. Specific gravity values determined in our laboratory were 1.937 and 1.948. The value determined by CCL, Belleville, using a Beckman air pycnometer was 1.82. Blaine specific surface determined by CCL, Belleville, was 282 m^2/kg.

MIX PROPORTIONING

Trial Mixes

A total of fourteen trial mixes were made between November 20 and December 18, 1980, eight cylinders being cast in each case for 7, 14 or

TABLE 4a - Chemical Analyses of Fly Ash

Compound	Source (1)	Source (2)	Source (3)
S_iO_2	56.8	57.7	52.78
Al_2O_3	19.6	22.5	22.14
Fe_2O_3	5.2	6.1	5.01
CaO	12.1	5.5	10.72
MgO	1.2	1.7	2.06
K_2O	1.1	2.1[a]	0.84
Na_2O	5.3		3.28
SO_3		0.37	0.50
TiO_2			0.43
P_2O_5			0.51
SrO			0.52
Loss on ing.		0.31	0.93 (1050°C)

(1) 1976 atomic absorption analysis conducted by the National Research Council

(2) Average of of four recent analyses provided by the supplier

(3) June 1981 x-ray fluorescence analysis conducted by CCL, Belleville, Ontario

(a) Alkalis available as Na_2O (ASTM C150)

TABLE 4b - Physical Properties of Fly Ash

Percent retained on No. 325 sieve	= 26.1%
Pozzolanic activity index with cement	= 78%
Pozzolanic activity index with lime	= 1025 psi
Autoclave expansion	= 0.04%
Specific gravity (varies considerably in the range 1.7-2.0)	= 1.77

28-day tests. The corrected mix proportions based on the measured unit weights (fresh state) together with other properties are shown in Table 6. The trials took place in chronological order A to L, mixes A, C, E, G, I and K with a cement content (nominal) of 400 kg/m^3, and mixes B, D, F, H, J and L with 500 kg/m^3 (nominal) of cement. The progression from A to K represents the development of a mix with the minimum possible fines to avoid segregation at the required slump and air content. Clearly, the fines could not be further reduced for this 400 kg/m^3 series of mixes, and mix K was used as the basis for proportioning mix A1 of the main series. For the 500 kg/m^3 series, harshness and the tendency to segregate were less noticeable, and mix L represents the mix with the lowest fines of the series B to L. In fact, the volumetric fraction of mortar (sand + cement + water) is the same for mix L as for mix K. Mix L was used as the basis for proportioning mix A3 of the main series with adjustments to the water and admixture dosages to get the required slump and air content.

It should be noted that consignment 1 of lightweight aggregate and the last of an existing delivery of cement were employed in the trial mixes. A new batch of cement and the second consignment of lightweight aggregate were used throughout the main series of mixes.

Main Series

Nominal mix proportions for series A, B, and C, as referenced in the work statement, are given in the raw data sheets. Mixes A1 and A3 developed from the trial mixes are the data base for series A. Mixes A2 and A4 reflect the increases in sand and water contents needed to substitute for

TABLE 6 - Trial Mix Characteristics

Mix Ref.	Unit wt. kg/m^3	Mix Proportions - kg/m^3				Slump -mm	Air - %	Comp. Strength - MPa			Fine/ Total agg.
		13 mm[(a)]	Sand	Cem.	Water			7-day	14-day	28-day	
A	1913	608	738	405	162	70	4.3	26.67	28.92	-	54.8
B	1927	595	670	496	166	105	3.5	24.63	26.68	-	53.0
C	1892	624	682	398	188	95	4.5	23.55	25.50	-	52.2
D	1913	608	637	490	178	80	5.3	29.62	30.95	-	51.2
E	1934	573	775	396	191	108	6.0	24.68	26.51	-	57.5
F	1962	575	701	489	196	80	4.8	31.12	32.87	-	54.9
G	1920	667	652	410	192	120	5.5	25.23	27.93	-	48.4
H	1952	642	614	501	195	108	4.8	27.72	30.50	-	48.9
I	1927	677	680	385	184	80	5.3	26.93	28.83	-	50.1
J	1929	675	593	470	192	92	4.0	30.07	31.77	-	46.8
K	1939	676	676	404	183	102	5.3	-	28.24	30.96	50.0
K[(b)]	2026	694	749	414	168	10(160)	3.5	-	35.84	37.77	51.9
L	1924	669	565	495	195	80	4.3	-	32.20	35.04	45.8
L[(b)]	1991	683	630	506	172	25(90)	3.0	-	36.98	39.44	48.0

(a) Lightweight aggregate weighed in SSD condition after pre-soaking.

(b) Low slump versions of K and L made using the superplasticizer.

Mix	Comment
A	Low slump.
C	Lowest strength at almost the correct slump.
E	High fines and relatively low strength.
G	Higher strength even at high slump. Harsh with a trace of segregation.
I	Slump a little low. Harsh with a trace of segregation.
K	Correct slump and air with relatively high strength. Fines minimum possible without excessive segregation.

a decrease in air content of about 3%.

Mix B7 is the base for series B and closely resembles trial mix $K^{(b)}$. It reflects an increase in the volume of sand over mix A1 to compensate for the estimated 25 kg/m^3 reduction in water content associated with redesign for 25 mm slump from 100 mm slump (trial mixes K and $K^{(b)}$). Nominal proportions for the remaining mixes in series B are based on volumetric reduction of the sand fraction by an amount equal to the estimated volume of fly ash included (assuming specific gravities of sand and fly ash of 2.65 and 2.00, respectively).

Mix C13 is the base for series C. It reflects an increase in the volume of sand over mix A3, but only to the extent of about 40% of the volume needed to compensate for the estimated 25 kg/m^3 reduction in water associated with redesign for reduced slump. In effect, the fine/total aggregate percentage is reduced a further 0.33% below that of trial mix $L^{(b)}$, and the volumetric fraction of mortar becomes almost identical to the corresponding fraction for mix B7. Nominal proportions for the remaining mixes in series C are based on volumetric reduction of the sand fraction by an amount equal to the estimated volume of fly ash included.

Mix proportions corrected from nominal values (data sheets) on the basis of saturated surface dry (SSD) unit weights are given in Table 7. This condition is selected in preference to unit weight in the fresh state since it most closely represents the unit weight and air content of the specimens as cast. Slump and air content for series B and C are the mean values for the two batches immediately after adding Mighty 150.

PROPERTIES OF FRESH CONCRETE

Full details of slump, air content, and other characteristics of each batch of fresh concrete are given on the primary concrete data sheets appended to this report. The slump values after addition of superplasticizer were maintained in the range 100 ± 20 mm (Table 7) with air contents in the range 4.5 ± 1.0% (Series A) and 5.0 ± 1.0% (Series B and C), as specified, except for mix B7 which was 0.5% higher. The influence of the amounts and proportions of fly ash and cement on the dosage of admixtures needed to produce nominally identical slumps and air contents in the various mixes is seen in Table 8. Since the dosage of superplasticizer in terms of percent by weight of cement plus fly ash remains essentially constant throughout, it appears that the admixture operates on fly ash much as it does on cement, despite differences in specific gravity and particle size distribution. In contrast, the dosage of air-entraining admixture increases significantly as the proportion of fly ash increases, reflecting the well-known effect of fly ash on the air-entrainment process.

PROPERTIES OF HARDENED CONCRETE

Full details of test results on individual specimens from each batch of concrete are given on the primary and supplementary concrete data sheets appended to this report. Only mean values for the mix as a whole are given in Table 8 to 15. Specimens other than freeze-thaw specimens were cured initially in a moist room for 7 days and were subsequently stored at 50% relative humidity until tested in accordance with ASTM C330, unless otherwise noted.

TABLE 7 - Mix Proportions & Properties (Main Series A, B and C)

Mix Ref.	Unit-wt-kg/m³				Corrected Mix Proportions-kg/m³					Slump -mm	Air -%
	Fresh	SSD	28-day Air-dry	Batch	13 mm agg.(c)	Sand	Cement	Fly Ash	Water		
A1	1973	1973	1924	1939	687	687	407	-	192	105	4.1
A2	2018	2015	1956	1982	686	722	407	-	200	120	1.6
A3	1941	1953	1914	1967	670	586	496	-	201	95	4.8
A4	1998	2008	1969	2016	672	623	498	-	215	100	1.7
B5	1943	1938	1897	1937	675	540	400	150	172	105	5.4
B6	1948(a)	1964	1921	1954	678	643	402	75	163	113	5.5(b)
B7	1947	1946	1897	1975	665	729	394	-	157	105	6.5
B8	1999	1983	1993	1940	690	732	358	51	152	103	5.3
B9	1984	1978	1936	1933	691	665	358	102	161	103	5.4
B10	1947	1940	1899	1917	683	591	354	152	160	101	5.1
C11	1910	1905	1869	1934	665	409	493	148	191	107	4.7
C12	1996	2000	1964	1944	694	530	514	77	185	110	4.6
C13	1989	1993	1954	1964	685	624	508	-	176	88	5.0
C14	1998	1999	1963	1925	701	579	467	78	174	116	4.8
C15	1950	1955	1920	1913	690	467	460	153	185	100	5.4
C16	1892	1893	1857	1895	674	357	450	225	188	103	5.0

(a) Batch 2 only

(b) Weighted mean value 2:1 to correspond to strength measurements

(c) SSD basis

TABLE 8 - Effect of Mix Proportions on Dosage of Air-Entraining Admixture

Mix Ref.	Darex ml/kg	Mi 150 % [b]	Fly ash/cement kg/m³
A1[a]	0.33	-	0/400
A3[a]	0.40	-	0/500
B5	1.82	0.49	150/400
B6	1.87	0.70	75/402
B7	1.41	0.56	0/394
B8	1.61	0.64	51/358
B9	1.66	0.65	102/358
B10	1.82	0.59	152/354
C11	2.06	0.57	148/493
C12	1.74	0.64	77/514
C13	1.40	0.59	0/508
C14	1.83	0.58	78/467
C15	2.27	0.54	153/460
C16	2.39	0.51	225/450

[a]Mixes A1 and A3 require much less because of higher slump

[b]Percent by weight of cement plus fly ash

Compressive Strength

Compressive strength and modulus of elasticity were determined on 152 x 305 mm cylinders at the ages specified in accordance with ASTM Method C39 and C469 respectively. The results summarized in Table 9 are mean values for sets of three specimens. The average coefficient of variation for compressive strength was 3.8%, indicating very good control in terms of overall-test variability according to ACI 214, and for elastic modulus was 3.0%.

Flexural and Splitting Strengths

Mean values of splitting strengths determined on sets of three 152 x 305 mm cylinders tested at 28 days in accordance with ASTM C496 are given in Table 10. The average value of the coefficient of variation for sets of three specimens was 7.1%.

Flexural strengths were determined, as specified, on pairs of 381 x 76 x 76 mm prisms the same as those employed for freeze-thaw testing. The prisms were tested in accordance with ASTM C78 over a 302 mm span at an age of 14 days (the start of freeze-thaw testing) and at the conclusion of freeze-thaw (age 24-32 days). The specimens were continuously moist-cured until tested. Since they were tested only in pairs, the computation of coefficients of variation was not considered useful.

Unit Weight

Unit weight was determined on the freshly mixed concrete, on the hardened concrete in the saturated-surface-dry (SSD) condition, and on the hardened concrete at an age of 28 days, 21 of which were at 50% relative humidity (ASTM C567). On average, the unit weights in the freshly mixed and hardened SSD conditions differ by only 0.03%, i.e. they are for practical purposes equal (Table 7). On average, the air-dry unit weights are 1.95%, or for practical purposes about 2% lower than the SSD values (Table 7).

TABLE 9 - Compressive Strength and Modulus of Elasticity

Mix Ref.	Compressive Strength - MPa					Modulus at 28 days-GPa	Fly ash/ceme -kg/m^3
	1 day	7 days	28 days	91 days	1 year		
A1	15.9	-	34.1	39.4	-	17.9	0/407
A2	15.0	-	34.3	39.4	-	17.4	0/407
A3	22.1	-	36.8	41.6	-	17.9	0/496
A4	21.2	-	38.4	42.4	-	18.1	0/498
B5	19.4	29.1	36.9	38.2	44.2	16.7	150/400
B6	22.3	31.0	38.9	42.3	48.5	17.3	75/402
B7	17.9	28.0	33.8	38.8	41.4	16.9	0/394
B8	19.0	29.8	36.9	42.9	46.6	18.6	51/358
B9	18.6	31.6 31.2[a]	38.8	43.5 42.7[b]	49.4	17.9	102/358
B10	18.1	28.9	38.1	40.8 41.6[b]	44.6	16.7	152/354
C11	25.0	31.3	38.7	42.0 41.3[b]	41.7	16.6	148/493
C12	28.8	34.5	41.7	46.8	53.1	19.0	77/514
C13	26.9	34.5	40.6	44.5	48.9	19.4	0/508
C14	24.4	34.2 33.8[a]	42.0	45.3	52.0	19.0	78/467
C15	22.2	31.7	38.2	42.6 44.5[b]	48.0	16.8	153/460
C16	20.6	30.5	36.4	38.6 43.1[b]	40.4	15.7	225/450

[a]Hand-rodded rather than vibrated

[b]Continuously moist cured

TABLE 9 - Compressive Strength and Modulus of Elasticity

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A1	15.9	-	34.1	39.4	-	17.9	0/407
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A3	22.1	-	36.8	41.6	-	17.9	0/496
A4	21.2	-	38.4	42.4	-	18.1	0/498
B5	19.4	29.1	36.9	38.2	44.2	16.7	150/400
B6	22.3	31.0	38.9	42.3	48.5	17.3	75/402
B7	17.9	28.0	33.8	38.8	41.4	16.9	0/394
B8	19.0	29.8	36.9	42.9	46.6	18.6	51/358
B9	18.6	31.6 31.2[a]	38.8	43.5 42.7[b]	49.4	17.9	102/358
B10	18.1	28.9	38.1	40.8 41.6[b]	44.6	16.7	152/354
C11	25.0	31.3	38.7	42.0 41.3[b]	41.7	16.6	148/493
C12	28.8	34.5	41.7	46.8	53.1	19.0	77/514
C13	26.9	34.5	40.6	44.5	48.9	19.4	0/508
C14	24.4	34.2 33.8[a]	42.0	45.3	52.0	19.0	78/467
C15	22.2	31.7	38.2	42.6 44.5[b]	48.0	16.8	153/460
C16	20.6	30.5	36.4	38.6 43.1[b]	40.4	15.7	225/450

[a]Hand-rodded rather than vibrated

[b]Continuously moist cured

Drying Shrinkage

Drying shrinkage was determined by recording the change in length of sets of three 286 x 76 x 76 mm prisms for each mix according to ASTM C157, except that the age at which drying at 50% relative humidity commenced was 7 days in accordance with ASTM C330. The original intent to monitor length change over a one year period of drying was unfortunately interrupted because the length comparator was tampered with by an unknown party between August 14 and September 14 resulting in the zero reading being changed. Readings were continued following this mishap, but only the length change relative to the new datum could be measured directly. The pattern of length change at later ages can only be estimated by linear interpoaltion over the missing time interval, as shown in Fig. 1. However, it appears that a relatively small proportion of the total shrinkage took place at later ages, much of the measured shrinkage occurring within 100 days of drying. Indeed, the marked decrease in the rate of change of length with time between 40 and 60 days is not untypical of shrinkage-time relationships shown in the literature.

Values of the average drying shrinkage, estimated using Fig. 1, are identified for each mix in Table 11 at drying times of 28 and 100 days in accordance with ASTM C330.

Creep

Creep was evaluated by recording deformations on pairs of specimens moist cured for 28 days prior to loading under conditions of 50% relative humidity in accordance with ASTM C512. A constant pressure hydraulic loading system producing a compressive stress of 10.1 MPa was used for all pairs of loaded specimens, giving the stress/strength ratios at time of loading shown in Table 12. Deformations were also monitored on companion pairs of unloaded control specimens cured and tested under the same conditions.

TABLE 11 - Drying Shrinkage at 50% Relative Humidity

Mix Ref.	Shrinkage-με			Water in mix-kg/m^3
	28 days	100 days	6 months	
B5	450	745	830	172
B6	545	810	890	163
B7	495	740	812	157
B8	468	740	822	152
B9	462	735	798	161
B10	485	740	810	160
C11	300	620	*	191
C12	375	690	*	185
C13	320	640	745	176
C14	460	770	*	174
C15	420	720	*	185
C16	515	825	*	188

*Value unconfirmed due to problems with the length comparator

TABLE 12 - Summary of Creep and Related Data

Mix Ref.	Elastic strain-με	Modulus GPa	El. strain x Modulus[c]-MPa	Stress/ Strength%	Creep at 28 days-με Actual[a]	Creep at 28 days-με Corrected[b]	Creep at 1 year-με Actual[a]	Creep at 1 year-με Corrected[b]	Shrinkage at 1 year-με[d]
B5	629	16.7	10.50	27.37	430	393	760	694	355
B7	580	16.9	9.80	29.88	520	435	1025	858	592
B10	587	16.7	9.80	26.51	385	363	680	641	309
C11	622	16.6	10.33	26.10	450	431	905	867	197
C13	492	19.4	9.54	24.88	330	332	645	648	558
C16	667	15.7	10.47	27.75	460	414	890	802	104

[a]Estimated from Fig. 2

[b]Corrected to a stress/strength ratio of 25% assuming direct proportionality between stress/strength ratio and creep

[c]Values should compare with the applied stress of 10.1 MPa

[d]Based on deformation of unloaded control specimens

Creep strain was computed as (total strain - elastic strain - shrinkage strain in the unloaded control specimen), as is the normal practice, and the creep-time relationships in Fig. 2 were developed on this basis. Table 12 compares the behavior of the various mixes in terms of elastic strain, stress/strength ratio at the time of loading (age 28 days), and creep corrected to a stress/strength ratio of 25%. However, since the creep values in Table 12 and Fig. 2 both depend on the deformation behavior of the unloaded control specimens, some apparent anomalies in the latter should be noted before reaching conslusions about comparative creep behavior. Considering that mixes B5, B7 and B10 have nearly identical shrinkage characteristics (Table 11), the spread of 1 year data for the unloaded control specimens (Table 12) is unusual. Likewise, any differences in shrinkage between mixes C11, C13, and C16 (Table 11) are not nearly as large as the differences for the unloaded control specimens (Table 12). The explanation appears to involve clearly visible hair cracking in some specimens, notably those containing 400 kg/m^3 or more of cement with fly ash (mixes B5, C11, and C16). The unloaded control specimens of mixes B7 and C13, which do not contain fly ash, have undergone a deformation of 550-600 $\mu\varepsilon$ over 1 year of drying while the values of mixes with fly ash are much lower (Table 12), presumably due to "spring-back" as a result of the observed cracking. Considering that the creep specimens were loaded and monitored only after 21 days of drying, the deformation of the unloaded specimens should be of the order of the difference between the 1-year shrinkage (850 to 950 $\mu\varepsilon$) and the 21-day shrinkage (250-400 $\mu\varepsilon$)(Fig. 1), i.e. 550-600 $\mu\varepsilon$. Since this applies only to mixes B7 and C13, it seems reasonable to conclude that only for these mixes is the creep data in Fig. 2 and Table 12 truly representative of creep behavior.

Freeze-Thaw Evaluation (ASTM C666 Procedure A)

Freeze-thaw performance was evaluated initially in accordance with ASTM C666 Procedure A, which specifies 14 days of moist curing followed immediately by freeze-thaw cycles. Performance under these conditions was very poor for all eight mixes with the relative dynamic modulus reaching 60% (the test end point) in less than 100 cycles (Fig. 3). The durability factors computed using Fig. 3 are also rather low (Table 13). Subsequently, high air content (7.5%) versions of mixes A1 and B7 were also evaluated to ascertain if the relatively low air contents (5 ± 1%) specified initially were a factor. However, performance was no better (Table 13), indicating that, as the paste is well protected at such a high air content, the fully saturated condition of the aggregate prior to testing was the governing factor.

Freeze-Thaw Evaluation (Modified ASTM C666)

To evaluate concrete performance under conditions more representative of those encountered in the field when using semilightweight concrete in structural applications, further testing was specified under contract OSU 81-00212. In this program, the normal 14-day moist curing cycle was altered to 14 days moist curing, followed by 11 days drying at 50% relative humidity, and 3 days moist curing prior to testing. Under these conditions performance improved greatly, with almost all specimens showing no significant deterioration within 300 cycles in terms of relative dynamic modulus (Table 14). All mixes meet the 80% minimum durability factor criterion normally associated with satisfactory performance. However, there is perhaps a slight indication, both here and in Table 13, that mixes with fly ash do not perform quite as well as those with cement only.

TABLE 13 - Freeze-Thaw Performance (C666 Proc. A)

Mix Ref.	DF_{300} (C666)			Air %
	Spec. 1	Spec. 2	Mean	
A1	11.0	16.8	13.9	4.1
A3	21.6	19.6	20.6	4.8
B5	13.4	11.8	12.6	5.4
B7	20.8	17.0	18.9	6.5
B10	8.2	6.0	7.1	5.1
C11	9.8	15.0	12.4	4.7
C13	18.4	12.0	15.2	5.0
C16	13.2	9.2	11.2	5.0
A5	13.0	14.8	13.9	7.5
B7R	20.4	16.6	18.5	7.5

TABLE 14 - Freeze-Thaw Performance (Modified C666)

Mix Ref.	Rel. Dyn. Modulus - %			Air %
	Spec. 1	Spec. 2	Mean[a]	
A1	100.5	102.6	101.6	4.1
A3	100.0	98.9	99.5	5.2
B7	97.6	98.7	98.2	6.2
B10	101.7	67.7	84.4	4.7
C13	103.1	101.4	102.3	4.8
C16	87.0	*	*	4.3

*Specimen 2 dropped

[a]Equals DF_{300}

Supplementary Compressive Strength and Related Data

Mixes A1R and B7R were cast to detect any major changes in the raw materials between the beginning and the end of the main casting program (January 12-March 17, 1981). Supplementary mixes identified as A1S to C16S, cast between August and December 1981, primarily for the modified freeze-thaw evaluation under contract OSU 81-00212, also provide additional strength and other relevant data (Table 15). Comparison of data for equivalent mixes using the average difference parameter (value obtained in supplementary test minus the original value) show that, although air contents increased very slightly (0.11% on average), strengths also increased by 3.1% at 7 days and 6.8% at 28 days. This is apparently associated with an increase of the order of 1% in unit weight which is probably due to an increase in the unit weight of the aggregate, since air contents have remained essentially unchanged. However fly ash variability could also contribute. For subsequent analysis of strength data, the differences in strength are considered small enough to treat the data from both contracts as comparable.

PRELIMINARY CONCLUSIONS

The following conclusions are preliminary in nature, and may be subject to modification following further detailed analysis of the relatively large amount of data generated. They are not necessarily valid quantitatively or qualitatively for all possible combinations of cements, fly ashes, and superplasticizers.

1. The superplasticizing admixture employed in the program (Mighty 150) seems to operate on fly ash in fresh concrete much as it does on cement.
2. Fly ash present in addition to the cement alone can improve the level of compressive strength attainable by 15-20%. Likewise, replacement of up

TABLE 15 - Supplementary Data

Mix Ref.	Compressive Strength - MPa			Air %	Unit weight - kg/m³		
	1 day	7 days	28 days		Fresh	SSD	Air-dry
A1R		26.4	33.5	5.2	2006		
(A1)			(34.1)	(4.1)	(1973)		
B7R		30.9	37.5	7.5	2009	2030	1985
(B7)		(28.0)	(33.8)	(6.5)	(1947)	(1946)	(1897)
A1S	18.6		37.9	4.1	1985	1992	1941
(A1)	(15.9)		(34.1)	(4.1)	(1973)	(1974)	(1924)
A3S	22.3		40.1	5.2	1942	1961	1918
(A3)	(22.1)		(36.8)	(4.8)	(1941)	(1953)	(1914)
B7S	20.3		38.1	6.2	1956	1988	1937
(B7)	(17.9)		(33.8)	(6.5)	(1947)	(1946)	(1897)
B10S	15.3		37.7	4.7	1949	1948	1897
(B10)	(18.1)		(38.1)	(5.1)	(1947)	(1940)	(1899)
C13S	28.1		42.1	4.8	1977	2010	1971
(C13)	(26.9)		(40.6)	(5.0)	(1989)	(1993)	(1954)
C16S	20.7		40.3	4.3	1879	1875	1840
(C16)	(20.6)		(36.4)	(5.0)	(1899)	(1893)	(1957)
Diff.	3.1%		6.8%	0.11%	0.56%	1.16%	1.10%

to 30% of the weight of the cement with fly ash appears possible in certain mixes with little or no loss of strength, particularly at ages of 7 days or more. Further analysis of the results in terms of fly ash/cement proportions, total amount of cementitious material, strength, and strength/weight ratio are needed to establish optimum mix parameters.

3. The 28-day modulus of elasticity appears to increase with the level of concrete strength in much the same way as for normal concrete.
4. Splitting and flexural strengths remain largely unaltered by the presence of fly ash and superplasticizer.
5. Shrinkage and creep data are inconclusive in some respects but certainly do not give any clear indication that the presence of fly ash adversely effects these properties.
6. Freeze-thaw tests show that this type of semilightweight concrete, with or without fly ash or the superplasticizer, cannot pass the ASTM C666 Proc. A test if the aggregate is presoaked before mixing takes place. However, if the concrete is allowed to dry before resoaking prior to the test, as would likely happen in many of its applications, freeze-thaw performance is generally satisfactory, although some mixes with high fly ash contents did not perform quite as well as those without fly ash.

POOR

QUALITY

ORIGINAL